NASA SP-5921 (01)

TECHNOLOGY UTILIZATION

LOW TEMPERATURE MECHANICAL PROPERTIES OF VARIOUS ALLOYS

A COMPILATION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TECHNOLOGY UTILIZATION OFFICE 1970
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

For sale by the National Technical Information Service, Springfield, Virginia 22151 – Price $1.00

Foreword

The National Aeronautics and Space Administration has established a Technology Utilization Program for the dissemination of information on technological developments which have potential utility outside the aerospace community. By encouraging multiple application of the results of its research and development, NASA earns for the public an increased return on the investment in aerospace research and development programs.

This publication, part of a series intended to provide such technical information, reports various low-temperature mechanical properties of some 20 alloys, most of which are high in strength and resist corrosion; the usual range of temperatures is from 70° to 423°F.

Apart from their interest to metallurgists these data bear on the suitability of these alloys for storage vessels, pumps, and other handling equipment for corrosive or noncorrosive liquids or gases at normal and cryogenic temperatures. Most of the data are quite new because hitherto no organization has had both the necessary resources and the urgent need to explore the field of cryogenics.

Additional technical information on individual metals can be requested by circling the appropriate number on the Reader's Service Card included in this compilation.

Unless otherwise stated, NASA contemplates no patent action on the technology described.

We always appreciate comment by readers and welcome hearing about the relevance and utility of the information in this compilation.

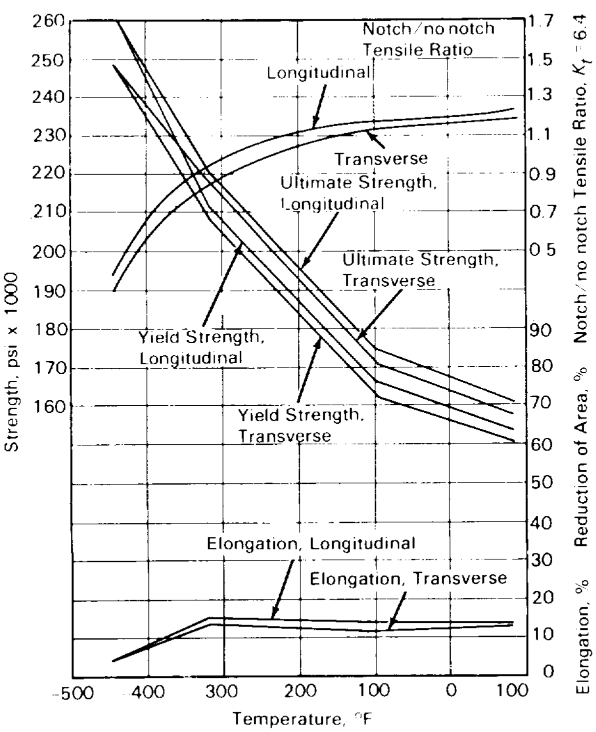
Ronald J. Philips, *Director*
Technology Utilization Office
National Aeronautics and Space Administration

Contents

Section 1. Steels

AISI-4340 PLATE (AMS-6359) BETWEEN 70° AND -423°F

The specimens were cut from 0.25-inch plate heat-treated to a strength of from 160,000 to 180,000 lb/in^2 (spec. MIL-H-6875). The scatter of data was generally less than 5% (see fig.).



Cryogenic Mechanical Properties of AISI-4340

The steel is not notch sensitive at -300°F or higher temperatures but becomes very sensitive at the temperature of liquid hydrogen. The material tested was on the low side of the heat-treatment range; an increase in strength to the high side could shift the notch-sensitivity transition to slightly higher temperatures. Because of the high notch sensitivity at such temperatures, hardware used at between -300° and -423°F should be free of stress risers such as nicks, scratches, and tool marks, especially in areas subject to bending stresses.

This heat of AISI-4340 showed no directional properties in the plate tested. The heat-treatment range reduces ductility to from 3 to 5% at -423°F. Notch-sensitivity transition occurs below -300°F in configurations containing a stress concentration of K_t=6.4.

Source: T. Gottlieb of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18288)

Circle 1 on the Reader's Service Card.

ARMCO 21-6-9 PLATE (Cr-Ni-Mn) AT 70°, -110°, -320°, AND -423°F

Tensile specimens were cut from a plate 4.75 inches thick and 50 inches wide that had been annealed for 1 hour at 1950°F and quenched with water. Longitudinal specimens were cut parallel with the rolling direction; long-transverse specimens, normal to the sides of the plate; center specimens, from the center of the plate's thickness; and intermediate specimens, from midway between the center of the thickness and the surface.

Toughness was adequate down to -423°F in both the longitudinal and long-transverse direc-

Mechanical Properties of ARMCO 21-6-9 at Four Temperatures

Specimen		Tensile strength, 1000 lb/in²		Elongation[b], in %		Reduction	V-notch		Keyhole	
Direction[a]	ARMCO No.	Yield, 0.2%	Ultimate	1 in.	2 in. %	in area, No.	ARMCO No.	Charpy ft-lb	ARMCO No.	Charpy, ft-lb
					70°F					
LTC	TC	55.8	101.6	52		73.9	TC	218.5	TC	97.0
LTC	TC	54.2	101.2	55		73.5	TC	192.0	TC	89.5
LTI	TI	60.5	102.5	47		65.0				
LTI	TI	57.0	103.0	50		74.6				
LGC	LC	57.2	102.8	55		79.7	LC	>240	LC	145.5
LGC	LC	57.0	102.6	55		78.4	LC	>240	LC	128.5
LGI	LI	54.2	101.8	54		80.2				
LGI	LI	55.2	99.8	54		80.0				
					-110°F					
LTC	TC3	81.5	131.5	57	42.0	69.5	TC3	146	TC8	61
LTI	TI3	87.0	134.4	59	43.5	71.0	TI1	146	TI4	60
LGC	LC3	88.7	131.8	60	45.5	73.5	LC3	211	LC8	93
LGI	LI3	82.0	129.0	60	43.0	76.0	LI1	215	LI4	75
					-320°F					
LTC	TC4	129.0	216.0	34	27.0	31.5	TC4	50	TC9	41
LTI	TI4	149.9	203.0	19	13.0	24.0	TI2	65	TI5	37
LGC	LC4	151.3	220.0	37	34.0	32.0	LC4	100	LC9	56
LGI	LI4	130.4	218.0	45	36.5	33.5	LI2	90	LI5	53
					-423°F					
LTC	TC5	166.5	243.0	17	11.5	28.0	TC5	41	TC10	39
LTI	TI5	195.5	245.0	15	10.0	20.5	TI3	53	TI6	34
LGC	LC5	192.9	253.0	16	12.0	22.0			LC10	47
LGI	LI5	160.7	229.0	19[c]	14.0	70.0	LI3	72	LI6	48

[a]LTC, long-transverse, center; LTI, long-transverse, intermediate; LGC, longitudinal, center; LGI, longitudinal, intermediate. [b]Specimen's diameter, 0.25 in. [c]Specimen failed outside the 1-in. gage length.

tions (see Table). The very high impact strength at 70°F decreased rapidly at lower temperatures but was never less than 34 ft-lb. Yield strength at 70°F was about 35% higher than typical values for CRES-347 and CRES-310. Both yield and ultimate strengths increased rapidly with fall in temperature.

Source: C.O. Malin of North American Rockwell Corp. under contract to Marshall Space Flight Center (MFS-18243)

Circle 2 on the Reader's Service Card.

CAST A-286 AT 70°, -110°, -320°, AND -423°F

Vacuum-investment-cast test bars, already annealed and machined, were homogenized for 2 hours at 2000°F and quenched in oil. All bars were then solution annealed for 1 hour at 1800°F; bars 1 25 (Tables 1 and 2) were then air cooled (condition-X), while bars 26 50 were quenched in oil (condition-Y). This difference in treatment showed no significant effect. After age hardening for 16 hours at 1325°F in air, the bars' hardness was RB-98.

The results of chemical analysis of the bars are compared in Table 3 with two specifications. The manganese content found is lower than the published nominal content (0.75%) which also is lower than the requirement for bars and forgings. It may be that vacuum-melted castings, low in sulfur and dissolved gases, do not require as high a manganese content.

Microphotography of the threaded section of bar-23 shows microshrinkage which explains the low ductility and tensile strength of several test bars; X-ray photographs, furnished by the supplier, did not clearly show these small voids. It may be that these defects can be eliminated by better foundry practice; meanwhile, however, A-286 should not be used for critical castings without thorough evaluation of the actual parts.

Elongation values at 70°F do not indicate a reliable ductile material; it is believed that other cast materials now under investigation will be superior.

Source: C.O. Malin of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18237)

Circle 3 on the Reader's Service Card.

Table 1. Mechanical Properties of Cast A-286

Test temp., °F	Bar, No.	Tensile strength, 1000 lb/in², Yield, 0.2%	Tensile strength, 1000 lb/in², Ultimate	Elongation in four diams, %	Reduction in area, %
		Condition–X			
70	1	79.0	93.3	4	11.5
"	2	76.4	109.9	9	14.0
"	3[a]	74.4	77.6	2	10.5
-110	4[a]	75.9	96.5	7	9.5
"	5	80.9	123.2	12	12.5
"	6	77.8	105.8	10	12.5
-320	7	95.5	122.3	10	13.0
"	8	92.7	114.6	10	11.5
"	9	94.1	127.8	13	17.5
-423	10	106.8	120.4	5	13.5
"	11	112.5	135.4	7	13.5
"	12	109.2	136.4	9	13.5
		Condition–Y			
70	26	71.9	108.1	13	19.0
"	27	74.5	105.1	10	14.5
"	28	73.4	107.4	12	24.0
-110	29	79.0	119.7	14	15.5
"	30	77.1	83.5	7	7.0
"	31	81.5	114.4	12	12.5
-320	32	69.3	69.3	00	0.0
"	33	88.1	93.7	4	5.5
"	34	89.0	111.9	11	15.5
-423	35	110.0	136.8	9	14.5
"	36	109.8	131.9	7	8.0
"	37	105.5	125.4	7	11.5

[a]Defect in bar; results are included in average.

Table 2. Notch Data on Cast A-286

Bar, No.	Test temp., °F	Tensile strength, 1000 lb/in² Notch, $K_t = 6.3$	Tensile strength, 1000 lb/in² Ultimate, av. (from Table 1)	Notch/no notch ratio, av.
		Condition-X		
13	70	145.5		
14	"	150.5	93.6	1.58
15	"	146.2		
16	-110	135.8		
17	"	157.2	108.5	1.40
18	"	163.3		
19	-320	178.3		
20[a]	"	104.5	121.6	1.26
21	"	176.9		
22	-423	188.9		
23	"	189.0	130.7	1.44
24	"	189.0		
		Condition-Y		
38	70	139.0		
39[a]	"	116.6	106.9	1.21
40	"	134.2		
41	-110	150.4		
42	"	151.7	105.8	1.41
43	"	146.4		
44	-320	162.0		
45	"	162.9	91.6	1.81
46	"	172.7		
47	-423	191.0		
48	"	189.4	131.4	1.43
49	"	184.7		

[a]Defect in bar; results included in averages.

Table 3. Chemical Composition (percentages) of A-286; Balance, Iron

Element	AMS-5734 for bar and forging	Supplier's spec.	This analysis
C	≤ 0.08	0.05	0.07
Mn	1.00-2.00	0.30	0.51
S	≤ 0.030	0.011	0.013
Si	0.40-1.00	0.78	0.70
Ni	24.00-27.00	26.62	26.4
Cr	13.50-16.00	14.73	13.82
Al	≤ 0.35	0.19	0.10
Mo	1.00-1.50	1.37	1.22
B	0.0030-0.010	0.008	0.003
P	≤ 0.040	0.018	0.005
V	0.10-0.50	0.21	0.29
Ti	1.90-2.35	2.04	2.04
Co		25	

CAST CD4MCu AT 70°, -110°, -320°, AND -423°F

Mechanical Properties of Cast CD4MCu; Four Specimens at Each of Three Temperatures.

Tensile strength, 1000 lb/in²					
Yield, 0.2%	Ultimate	Notch, K_t=6.3	Notch/ no notch ratio, av.	Elongation in four diams, %	Reduction in area, %
		70°F			
112.0	131.2	165.6	1.33	10.0	16.0
112.0	147.0	203.0		15.0	33.0
110.0	148.3	195.0		17.0	33.5
100.7	144.5	193.2		17.0	33.5
		-110°F			
116.2	164.8	153.3	0.94	20.0	36.0
126.3	170.6	185.4		18.0	33.0
116.2	162.8	111.2		20.0	36.0
121.6	158.1	165.8		6.0	8.0
		-320°F			
a	117.7	97.6	0.74	0.0	0.0
a	116.0	106.1		0.0	0.0
a	103.9	75.1		0.0	0.0
a	122.2	61.0		0.0	0.0

[a]Failed from brittleness before yielding 0.2%.

Vacuum-investment-cast test bars received in the annealed (2050°F for 30 min, with water quenching) and machined condition were aged at 900°F under argon. Because the material was very brittle at -320°F (see Table), further tests at -423°F were abandoned.

The material has good strength and toughness at room temperature, but its ductility and notch toughness decrease very rapidly at low temperatures. It should not be used at temperatures below -75°F.

Source: C.O. Malin of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18238)

Circle 4 on the Reader's Service Card.

CAST CRES-310 AND CRES-347 AT 70°, -110°, -320°, AND -423°F

The investment-cast, annealed, and machined tensile bars of each material came from three different heats. The CRES-310 bars were annealed for 1 hour at 2100°F under hydrogen and quenched in oil; the others were annealed for 1 hour at 1950°F under hydrogen and air cooled.

The properties of CRES-310 at 70°F (see Table) are considerably lower than the typical values published by International Nickel Co. The much larger grain size in CRES-310, revealed by the fractured bars, may explain its lower properties. The ductility of both metals is adequate at all temperatures; that of CRES-347 is the lower of the two.

Source: C.O. Malin of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18235)

Circle 5 on the Reader's Service Card.

Low Temperature Mechanical Properties of Cast CRES-310 and CRES-347

Tests, No.	Test temp., °F	Tensile strength, 1000 lb/in², Ultimate, High	Ultimate, Low	Ultimate, Av.	Yield, 0.2%, High	Yield, 0.2%, Low	Yield, 0.2%, Av.	Notch/ no notch ratio, av., $K_t = 6.0$	Elongation in 1 in., %, High	Elongation, Low	Elongation, Av.
					CRES-310						
(INC)[a]	70			76			38				37
6	70	62.1	55.4	57.9	26.9	25.2	25.9	1.64	60	42	51
5	-110	74.9	61.1	70.6	40.3	35.5	37.5	1.57	57	47	53
5	-320	111.9	83.4	96.8	71.8	67.1	69.2	1.49	60	26	37
7	-423	132.6	99.9	110.7	96.0	88.3	92.0		41	15	28
					CRES-347						
(INC)[a]	70			77			38				39
6	70	83.5	62.9	78.2	39.8	25.6	34.9		51	35	44
7	-110	127.0	105.5	115.6	50.5	42.2	45.5		45	30	35
7	-320	177.0	150.6	161.7	64.6	30.4	44.4		21	19	20
5	-423	161.6	145.0	154.8	68.6	41.2	54.2		19	15	17

[a]International Nickel Company's published typical values.

CAST 17-4PH, CONDITION H-1150M, AT 70°, -110°, -320°, AND -423°F

Low-Temperature Tensile Properties of Cast 17-4PH from Two Foundries

Test temp. °F	Tensile strength, 1000 lb/in², Ultimate	Yield, 0.2%	Notch, $K_t = 6.3$	Notch/ no notch ratio	Elongation in four diams, %	Reduction in area, %	Hardness, Rockwell-C
				Misco[a]			
-320	189.3	140.5			10.0	7.0	
70							19
-320	182.6	140.8			10.0	8.0	
				Austenal[b]			
70	118.9	84.1	187.4	1.57	15.0	35.5	23.5
-110	137.6	100.4	207.3	1.51	8.0	14.0	
-320	162.9	144.2	142.2	0.87	4.0	9.5	
-423	196.9	196.9	102.3	0.52	0	0	
				Austenal[c]			
70	117.5	82.5	180.3	1.53	15.0	36.5	22
-110	135.3	95.3	181.1	1.34	14.0	31.5	
-320	145.0	142.2	77.9	0.54	0.5	2.5	
-423	156.3	–[d]	80.7	0.51	0	0	

Heat treatments: [a]1 Hour at 1900°F, oil quenching; 2 hours at 1400°F, air cooling. [b]1.5 Hours at 2100°F, 2 hours at 1400°F, 4 hours at 1150°F; air cooling throughout. [c]1 Hour at 1900°F, 2 hours at 1400°F, 4 hours at 1150°F; air cooling throughout. [d]Specimen failed before 0.2% yield.

Two batches of tensile bars were tested: (1) vacuum-melted and vacuum-investment-cast bars solution annealed for either 1.5 hours at 2100°F or 1 hour at 1900°F, with air cooling (furnished by Austenal Foundry); (2) two bars melted and cast in air by the "monoshell" process and solution annealed for 1 hour at 1900°F, with oil quenching (furnished by Misco Precision Foundry).

Before the tensile tests, all bars were age hardened for 2 hours at 1400°F plus 4 hours at 1150°F, with air cooling throughout.

The 2100°F solution treatment seems to give better notch toughness and elongation than the 1900°F treatment (see Table). More recently the heat treatment of 17-4PH castings has been modified (particularly for the interface panel) and further tests will be required for evaluation of the effects of double solution annealing and low-temperature-transformation heat treatments. When cast 17-4PH is used below -200°F, its low notch toughness and low ductility must be provided for in the design.

Source: C.O. Malin of North American Rockwell Corp. under contract to Marshall Space Flight Center (MFS-18239)

Circle 6 on the Reader's Service Card.

FREE-MACHINING 300-SERIES CRES AT 70°, -110°, -320°, AND -423°F

Table 1. Tensile Properties of ⅛-in. and ¼-in Bars at Four Temperatures

Specimen or specification	Tensile strength, av., 1000 lb/in², Yield, 0.2%, ⅛-in.	Yield, 0.2%, ¼-in.	Ultimate, ⅛-in.	Ultimate, ¼-in.	Elongation, av., in four diams, %, ⅛-in.	¼-in.	Reduction in area, av., %, ⅛-in.	¼-in.
				70°F				
MIL-S-7720	>80.0		≥115.0		≥15	47	≥35	64.5
CB	103.3	94.6	124.0	121.8	42.5		64.0	
MRB	110.7	102.5	128.0	125.6	42.5	38	64.5	62.5
SB	125.7		132.0		39		61.5	
				-110°F				
CB		111.8		170		40		55.5
MRB		120.2		165.5		44		58.5
				-320°F				
CB		113.7		251.5		38		54.0
MRB		118.0		262.0		37		54.0
				-423°F				
CB		108.4		231.3		38		54.0
MRB		144.2		284.9		28		31.0

These steels come in two grades, 303S (containing sulfur) and 303Se (containing selenium to improve the machinability), available in either condition-A (annealed) or the high-tensile condition-B; they cannot be welded satisfactorily and are slightly less resistant to corrosion than are 300-series stainless steels, especially when heated beyond 700°F. In condition-B they lose both corrosion resistance and strength when heated beyond 700°F.

In condition-B material the increase in strength, effected by cold working, is greatest at the surface and is a function of depth. For this reason, undersized tensile bars (thread and reduced diameters of ¼ and ⅛ in., respectively) were cut from three locations within a 1-in.-diam bar of CRES-303S in condition-B: from the center (CB), from half the radial depth (MRB), and from immediately below the surface (SB). The hardness of the bar ranged in Rockwell-A from 64.5 at the surface to 62 at the center (Rockwell-C, 28.5 to 23). These specimens were tested at 70°F (Table 1).

Standard ¼ in.-diam (reduced section) tensile bars also were cut from the center and the half-radius depth of a 1-in.-diam bar of the same material; these were tested at 70°, -110°, -320°, and -423°F (Table 1).

The somewhat higher tensile strength of material from near the surface of a bar than from its center is taken into account by MIL-S-7720 for CRES-303S and CRES-303Se in condition-B

(Table 2); the minimum tensile properties are guaranteed for all areas within a bar of a given diameter. In condition-B, both steels have sufficient ductility for use at temperatures down to −423°F. In mechanical properties, CRES-303Se is believed to equal or exceed CRES-303S.

Source: C.O. Malin of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18241)

Circle 7 on the Reader's Service Card.

Table 2. Tensile Properties Specified by MIL-S-7720 for CRES-303S and CRES-303Se

Diam. of raw stock, in.		Tensile strength, 1000 lb/in² Yield, 0.2%	Tensile strength, 1000 lb/in² Ultimate	Elongation, %	Reduction in area, %
		Condition-A			
(All diams)			< 100.0	35	50
(Spec. QQ-S-763 CL 303)[a]		30	75	40	50
		Condition-B			
≤ 0.75		≥ 100	≥ 125	≥ 12	> 35
> 0.75–	< 1.0	≥ 80	> 115	≥ 15	≥ 35
> 1.0–	≤ 1.25	≥ 65	≥ 105	≥ 20	≥ 35
> 1.25–	≤ 1.5	≥ 50	≥ 100	≥ 28	≥ 45
> 1.5–	≤ 3	≥ 45	≥ 95	≥ 28	≥ 45
> 3		≥ 35	≥ 80	≥ 28	≥ 45

[a]Included for comparison

FORGED CRUCIBLE CG-27 AT 70° AND −320°F

Table 1. Chemical Specifications of CG-27; Balances, Iron.

Element	Specification, % General Electric	Specification, % This heat	Specification, % Rocketdyne
C	0.02–0.08	0.07	0.08
Al	1.45–1.75	1.59	1.57
Ti	2.3–2.7	2.48	2.56
Mo	5.0–6.0	5.69	5.62
Cb	0.6–1.1	0.70	1.06
Cr	12.5–14.0	12.96	13.64
Ni	37.0–39.0	38.45	38.37
B	0.003–0.015	0.010	0.0073
S	≤ 0.015	0.005	0.004
Mn	≤ 0.5	0.06	0.058
Si		0.12	0.19
P		0.005	0.018

A billet (Table 1), made by the double-vacuum-melting process and supplied in the solution-annealed condition, was cut into slices that were solution annealed by 1-hour heating in air at 1875°F before quenching in oil at ambient temperature. The hardness of the slices was 179 Brinell.

Charpy-impact and round-smooth and round-notch (K_t=6.3) tensile specimens were machined from the slices. The specimens represented longitudinal, long-transverse, and short-transverse grain flow; they were double aged by 16-hour heating in air at 1450°F, with air cooling, before 16-hour heating in air at 1200°F that was followed by air cooling. The hardness was Rockwell C-39 after aging (see Table 2).

Source: E.F. Green of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18283)

Circle 8 on the Reader's Service Card.

Table 2. Mechanical Properties of CG-27

Test temp., °F	Grain Flow[a]	Tensile strength, 1000 lb/in² Yield, 0.2%	Ultimate	Notch (K_t=6.3)	Elongation, %, in 1 in.	0.5 in.	Reduction in area, %	Notch/no notch ratio	Charpy, ft-lb
70	L	145.5	191.0	214.0	18.0	20.0	24.4	1.12	10.0
70	L	140.5	190.4	224.0	18.0	20.0	23.8		10.0
70	L	138.8	190.5	202.0	18.0	21.0	25.6		12.0
-320	L		207.9	214.0	10.0	12.0	11.0	1.04	7.0
-320	L	161.8	208.4	219.0	11.0	10.0	11.0		6.0
-320	L	157.2	209.0	215.0	11.0	12.0	7.4		7.0
70	LT	140.3	189.2		14.0	16.0	18.4	1.10	8.0
70	LT	140.5	188.5	209.0	12.0	16.0	16.9		6.0
70	LT	136.9	190.0	209.0	16.0	20.0	21.0		6.0
-320	LT	155.8	204.5	197.8	10.0	12.0	9.5	0.98	4.0
-320	LT	153.8	197.0	198.0	8.0	12.0	7.9		4.0
-320	LT		206.0	201.0	10.0	12.0	11.8		4.0
70	ST	139.0	182.5	202.0	10.0	16.0	15.4	1.07	4.0
70	ST	137.0	190.0	199.0	14.0	16.0	17.0		5.0
70	ST	135.0	187.2	203.0	14.0	15.0	15.4		5.0
-320	ST	154.3	194.6	204.0	10.0	12.0	12.4	0.96	4.0
-320	ST	156.8	207.9	194.0	11.0	12.0	14.6		5.0
-320	ST		198.6	179.8	10.0	10.0	8.6		4.0

[a]L, longitudinal; LT, long transverse; ST, short transverse.

HP9-4-25 (9 Ni-4 CO) PLATE AND FORGING AT 70°, -320°, AND -423° F

Table 1. Chemical Specifications of HP9-4-25; Balance, Fe.

Element	Specified contents, % General	This heat	Rocketdyne
C	0.24–0.30	0.28	0.30
Mn	0.10–0.35	0.29	0.35
Si	0.10–0.35	0.10	0.13
P	< 0.010	0.005	0.010
S	< 0.010	0.005	0.006
Cr	0.35–0.60	0.53	0.50
Ni	7-9	8.26	7.83
Co	3.5-4.5	3.82	3.80
Mo	0.35–0.60	0.47	0.42
V	0.06–0.12	0.15	—

The material (Table 1) had been remelted in vacuum by arc, with consumable electrodes, and deoxidized with carbon. Smooth and notched (K_t=6.3) round tensile and V-notched Charpy-impact specimens were machined from slices cut from the center of a forged block and representing short-transverse and longitudinal grain flow. The block had been annealed to a Rockwell-C hardness of 31 from the as-received hardness of 42–44. Other specimens, representing longitudinal and transverse grain flow, were cut from 0.25-in. plate.

The specimens were then austenitized for 1 hour at 1500°F in a controlled atmosphere and oil-quenched to Rockwell-C 48. Double tempering for 2 hours plus 2 hours at 1000°F resulted in a finished hardness of Rockwell-C 43–44. Tensile and impact tests were made at 70°F and at the temperatures of liquid nitrogen and oxygen (Table 2).

Comparisons were made of the mechanical properties (1) at 70°F of samples receiving martensitic or bainitic heat treatment; (2) at cryogenic temperatures of HP9-4-25 and 18%-Ni (200-grade) maraging-steel plate.

These conclusions are drawn from the tests: As forging or plate, HP9-4-25 can develop high strength and retain toughness at temperatures down to −423°F. In strength at cryogenic temperatures it is slightly poorer than 18%-Ni maraging-steel plate. It must be coated for protection from corrosion.

Source: E.F. Green of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18282)

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Table 2. Mechanical Properties of HP9-4-25 at Three Temperatures

Grain-flow direction[a]	Test temp., °F	Tensile strength, 1000 lb/in² Yield, 0.2%	Ultimate	Notch	Elongation, %, in 2 in.	1 in.	0.5 in.	Reduction in area, %	K_t	Notch/no notch ratio	Charpy, ft-lb
					Forged block[b]						
L	70	192	211	313		16	23	61	5.8	1.48	42
L	-320	235	260	320		16	25	60	5.6	1.24	20
L	-423	259	270	221		32	47	38	5.8	0.85	23
ST	70	198	209	305		14	25	58	6.0	1.46	47
ST	-320	235	262	320		14	23	55	5.5	1.22	21
ST	-423	268	285	221		24	39	30	6.3	0.78	22
					Plate, 0.25 in.[c]						
L	70	191	204	243	12	20	34		6.5	1.19	
L	-320	241	260	292	8	11	19		7.3	1.12	
L	-423	267	273	286	8	15	28		7.4	1.05	
T	70	193	207	244	12	17	27		7.8	1.18	
T	-320	235	261	295	10	14	19		7.8	1.13	
T	-423	280	293	299	8	11	16		7.8	1.02	

[a]L, longitudinal; ST, short transverse; T, transverse. [b] Circularly notched for notch tests. [c]Edge-notched for notch tests.

18-PERCENT-NICKEL (200-GRADE) MARAGING PLATE AT 70°, −320° AND −423°F

Table 1. Chemical Specifications of 18-Percent-Nickel (200-Grade) Maraging Steel; Balance, Iron.

Element	Percentages Commercial	This heat	Rocketdyne
C	< 0.03	0.022	0.03
Mn	< 0.10	0.06	0.01
P	≤ 0.01	0.005	0.010
S	≤ 0.01	0.006	0.005
Si	< 0.10	0.04	0.06
Ni	17-19	17.76	17.39
Co	8-9	8.50	8.36
Mo	3-3.5	3.50	3.01
Ti	0.15-0.25	0.22	0.24
Al	0.05-0.15	0.12	0.07
Zr	0.02	0.02	0.02
B	0.003	0.003	0.010

The material (Table 1) had been remelted in vacuum with consumable electrodes. Tensile-test blanks representing the longitudinal rolling direction were machined and surface-ground to 0.200-in. thickness; half were edge-notched (K_t=6.3) before all were solution annealed in dry hydrogen for 1 hour at 1500°F and then rapidly cooled in hydrogen—equivalent to air cooling. Age hardening followed: 3 hours in hydrogen at 900°F.

The following conclusions are drawn (Table 2): At such temperatures this steel has greater fracture toughness than the high-yield-strength 250-grade, and much greater toughness than Hy-Tuf and AISI-4340 high-strength steels. The steel is qualified for consideration for cryogenic applications.

Source: E.F. Green of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18281)

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Table 2. Comparison of Mechanical Properties of Four Ultrahigh-Strength Steels at Three Temperatures

Test temp., °F	Hardness, Rockwell-C	Tensile strength, 1000 lb/in² Yield, 0.2%	Ultimate	Notch	K_t	Notch/no notch ratio	Elongation in four diams, %	Reduction in area, %
			18% Ni (200-grade), 0.25-in. plate					
70	44-45	208	214	268	6.5	1.25	8	
-320	"	272	282	355	6.5	1.26	6	
-423	"	307	308	359	6.6	1.13	5	
			18% Ni (250-grade), 0.25-in. plate					
70	48-52	258	265	313	6.2	1.18	7	
-320	"	328	339	365	6.4	1.07	7	
-423	"	364	372	137	6.4	0.37	5	
			Hy-Tuf, 0.75-in. bar					
70	47	193	231	330	6.0	1.43	15	50
-320	"	245	281	211	6.0	0.75	14	33
-423	"	292	317	-[a]	6.0	-[a]	2	0.5
			AISI-4340, 0.75-in. bar					
70	38	152	170	209	6.4	1.23	16	
-320	"	208	228	224	6.4	0.97	14	
-423	"	256	260	117	6.4	0.45	4	

[a]Breakage in threads indicated brittleness.

WROUGHT 17-4PH AT 70°, -110°, -320°, AND -423°F

Tested were (1) a 0.5-in.-diam bar (AMS-5643), (2) a 3.5 × 3.375 × 5-in. billet, (3) a 3.25 × 5.5-in.-diam pancake (North American Rockwell specification LB0160-133), and (4) a 9 × 9 × 15-in. forging (AMS-5643) (Tables 1 and 2). The forging was upset from a 7-in. cube forged from an 8-in. billet; the forging temperature was between 1850° and 2150°F. Four heat treatments were tested, with air cooling used throughout: (1) 4 hours at 1150°F (H-1150), (2) 2 hours at 1400°F plus 4 hours at 1150°F (H-1150M), (3) 2 hours at 1300°F plus 4 hours at 1150°F (H-1150ML), and (4) 2 hours at 1500°F plus 4 hours at 1150°F (H-1150MH). The last two treatments were tried because H-1150M did not give the claimed 28-ft-lb impact strength at -320°F; they had no significant effect.

Alloy 17-4PH in condition H-1150M should be considered for liquid-oxygen applications where cost is important; although not quite as strong as Inconel X-750 or Inconel-718, it is much stronger than CRES-347 (yield strength, 100,000 versus 35,000 lb/in²). Its excellent machinability is far better than that of CRES-347 or the Inconels.

In condition H-1150M this material has sufficient notch toughness at -320°F for most applications. For lower temperatures its low toughness should be specially considered in design; the same is true of H-1150 material for temperatures below -100°F.

Source: C.O. Malin of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18242)

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Table 1. Mechanical Properties of 17-4PH Variously Heat Treated

Test direction[a]	Temp., °F	Average tensile strength, 1000 lb/in² — Yield, 0.2% H-1150	Yield, 0.2% H-1150M	Ultimate H-1150	Ultimate H-1150M	Notch, $K_t = 6.3$ H-1150	Notch, $K_t = 6.3$ H-1150M	Notch/no notch ratio, av. H-1150	Notch/no notch ratio, av. H-1150M	Elongation in four diams, av., % H-1150	Elongation in four diams, av., % H-1150M
							0.5-in. Bar				
L	70	149.1	102.2	154.6	131.5	261.7	212.0	1.69	1.61	18	23
All	70	105.0		135–160						16	
L	-110	165.9	106.3	171.15	149.8	274.7	235.4	1.60	1.57	17	22
L	-320	204.5	148.8	211.5	203.7	149.6	243.4	0.71	1.19	17	29
L	-423	211.0	200.9	219.0	228.2	124.1	167.7	0.57	0.73	11	19
							Pancake				
L	70		89.9		126.7		195.7		1.54		19
T	70		90.7		124.7		194.2		1.55		21
L	-320		140.6		198.9		246.8		1.24		28
T	-320		141.7		197.8		248.2		1.25		28
L	-423		196.2		225.5		210.2		0.93		23
T	-423		193.3		205.0		121.0		0.59		10
							Billet				
T	70		109.0		146.3		214.1		1.46		16
T	-320		151.3		219.0		251.6		1.15		16
T	-423		205.3		218.6		173.1		0.79		4.2
							Forging				
L	70		102.2		129.6						18
L	-320		143.2		204.2						28

[a]L, longitudinal; T, transverse.

(Cont'd below)

Table 1. Mechanical Properties of 17-4PH Variously Heat Treated (cont'd)

Test direction[a]	Temp., °F	Reduction in area, av., % H-1150	Reduction in area, av., % H-1150M	Charpy V-Notch impact strength, av., ft-lb H-1150	Charpy H-1150M	Charpy H-1150ML	Charpy H-1150MH	Hardness Rockwell-C H-1150	Hardness H-1150M	Hardness H-1150ML	Hardness H-1150MH
L	70	66	72	57	114			33.5	28		
All	70	50									
L	-110	62	70	6	62						
L	-320	44	60	3	8						
L	-423	43	29	4	9						
L	70		56		69		65		25		25
T	70		61		32		53				
L	-320		41		13		20				
T	-320		44		4		8				
L	-423		18		8		19				
T	-423		10		5		9				
T	70		42								
T	-320		29								
T	-423		7								
L	70		65			97	57		27	28	28.5
L	-320		36			10	7				

Table 2. Chemical Composition (percentages) of 17-4PH; Balance, Iron.

C	Mn	P	S	Si	Cr	Ni	Cu	Cb
Spec. AMS-5643								
≤0.07	≤1.0	0.040	0.030	≤1.0	15.50–17.50	3.0–5.0	3.0–5.0	0.15–0.45
Analysis of 0.5-in. bar								
0.035	0.26	0.029	0.008	0.49	16.20	4.12	3.31	0.30
Analysis of pancake								
0.04	0.60	0.01	0.022	0.48	15.60	4.42	3.34	0.27
Analysis of forging								
0.05	0.348	0.011	0.014	0.92	15.49	4.93	3.58	0.337

Section 2. Nickel Alloys

LARGE FORGINGS OF INCONEL-718 AT 70°, -110°, -320°, AND -423°F

An 18-in.-diam ingot, produced by vacuum-induction melting followed by consumable-electrode remelting, was first reduced to a 6-in.-diam.round and then forged to a 4 × 9 × 15-in. billet that was annealed at 1750°F. Test blanks cut from the forging were heated in either of two ways. Treatment-A: solution treatment for 45 min.at 1950°F was followed by air cooling; after double aging for 10 hours at 1400°F, they were furnace cooled to 1200°F, the total aging time being 20 hours. Treatment-B: solution treatment for 45 min at 1800°F was followed by air cooling; after double aging for 8 hours at 1325°F, they were furnace cooled to 1150°F, the total aging time being 18 hours. Smooth and notched (K_t=6.3) tensile bars and Charpy V-notch bars were then machined. The results form Tables 1 and 2.

Microphotography showed wide distribution of large precipitates of Lave's phase, Fe_2(Cb, Mo), in materials after both heat treatments; treatment-A resulted in less. A few blocky carbides and nitrides scattered throughout the material were distinguishable from the Lave's phase by their angular shape and different color.

The main structural differences resulting from treatment-A were the absence of an intergranular precipitate and a larger grain size; the higher temperature dissolved the intergranular precipitate and caused grain growth. Treatment-B gave significantly higher yield strength, notch toughness, and impact strength at all temperatures. Both treatments gave practically identical ultimate strengths.

The strength of the material was the same in all three directions. The indicators of ductility and toughness declined consistently from the longitudinal to the transverse direction. Toughness was adequate in all directions, but in some instances it decreased by more than 50% in the short-transverse direction.

Source: C.O. Malin of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18244)

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Low-Temperature Mechanical Properties of Ti-5 Al-2.5 Sn

Specimen, [a]No.	Ultimate	Yield 0.2%	Notch, K_t = 6.3, av.	notch ratio, av.	in 1 in., %
			-423°F		
L-23	210.8	189.4			9
L-24	207.3	190.9	208.0	1.02	3
L-25	194.7	175.0			6
T-24	206.2	191.6			8
T-28	204.2	172.8	197.2	0.97	6
T-30	202.3	181.5			8
ST-22	203.6	184.6			6
ST-27	191.0	-3[c]	204.1	1.01	3
ST-30	210.2	186.2			3
L-27	132.4	129.3			8
T-27	132.7	130.5			10
T-31	134.1	131.2	204.0	1.51	9
T-23	137.6	133.7			_[b]
ST-25	125.7	121.8			6
ST-28	133.7	129.2	213.9	1.61	7
ST-29	137.5	133.4			6
			-320°F		
L-16	181.3	164.7			_[b]
L-19	187.2	174.2	243.5	1.32	8
L-20	183.4	171.8			8
T-19	183.3	165.6			6
T-20	186.5	170.4	210.0	1.13	8
T-22	185.2	163.8			.8

[a]L, longitudinal; T, transverse; ST, short transverse. [b]Specimen fractured at or outside gage mark. [c]Erratic stress-strain curve; yield point could not be measured.

FORGINGS OF Ti-6 Al-4 V AT -423°F

Tensile Properties at -423°F of Annealed Ti-6 Al-4 V Forgings

Item	Modulus of elasticity, x 10^6 lb/in²	Strength, 1000 lb/in²: Yield	Strength, 1000 lb/in²: Ultimate	Reduction in area, %
Mean	21.6	240.3	258.1	26.8
S.D. of mean	0.2	1.0	0.6	1.5
Population S.D.	1.4	8.1	5.4	4.0
Lower limit of mean; 95% confidence	21.3	238.5	257.1	23.9

The tensile specimens came from 82 annealed forgings from seven heats from three manufacturers; analysis of the data shows no significant difference between heats.

Source: R.J. Davis and E.J. France of McDonnell Douglas Corp. under contract to Marshall Space Flight Center (MFS-12533)

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Section 4. Bronzes

CENTRIFUGALLY CAST ALUMINUM-BRONZE (85 Cu–11 Al–4 Fe) AT 70°, -320°, AND -423°F

Mechanical Properties of Cast Aluminum-Bronze at Three Temperatures

No.	Tensile strength, 1000 lb/in² Yield, 0.2%	Ultimate	Elongation, %, in 1 in.	2 in.	Reduction in area, %	Charpy-V, ft/lb	Hardness, Rockwell-B
			70°F				
1[a]	36.1	109.2	16	24	16.8	24	94
2[b]	40.1	112.8	14	20	15.1	22	92
3[a]	36.7	111.1	15	19	16.9	22	94
			-320°F				
4[b]	49.3	124.3	8	16	10.9	15	93
5[a]	49.6	135.2	10	20	13.1	14	97
6[b]	52.6	139.8	16	20	15.3	15	95
			-423°F				
7[a]	46.1	141.0	10	20	13.0	16	92
8[b]	48.5	139.2	16	20	15.3	14	95
9[b]	48.4	138.1	14	16	14.7	16	95
			Specified by QQ-B-671b				
	≥30	≥75		≥12			90

[a]From inner section [b]From outer section.

Specimens for testing (see Table) were cut from a 13-in. billet, 1.25 and 4.0 in. in inner and outer diameter, that complied chemically and mechanically with specification QQ-B-671b, class-C. Macroetching of transverse sections always showed fine-grain structure to within 0.25 in. of the bore.

Source: E.F. Green of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18246)

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CAST, LEAD-RICH BRONZES: BEARIUM B-10 AND BEARIUM B-4 AT 70°, -320°, AND -423°F

Tensile, Charpy V-notch, and dilatometer tests (see Table) were made of Bearium B-10 (70 Cu 10 Sn 20 Pb) and Bearium B-4 (70 Cu-4 Sn 26 Pb). Photography of the microstructure showed homogeneous distribution of the lead in globular form throughout the cast cross section; this feature may result from the addition of specially treated (gasified) lead to the copper-tin melt—untreated lead normally diffuses to the grain boundaries of the copper-tin matrix. Two balance-piston seals were inspected radiographically; both bronzes can be X-rayed, but interpretation is made difficult by the dispersion of lead.

For highly finished surfaces these alloys should be machined with Carboloy grade-44A or grade-883 rather than high-speed cutting tools; they should be cut at high speed with light feed and moderately deep cut to avoid tearing of the lead particles which makes the machined surface appear porous. Mineral oil containing 3.7% lard oil is used as a cutting coolant; sulfur-based coolants are never used. When it is lapped, the surface should not be charged with lapping compound.

Bearium B-10 is recommended as a replacement for graphite in high-pressure and low-pressure seals for the balance piston of the J-2 Mark-15 turbopump; it has greater strength in compression, greater resistance to pounding, and a lower rate of wear. Both bronzes are tougher than graphite impregnated with silver; Bearium B-10 wears more slowly than the other. Parts should be machined from separate castings so that lead-tin segregations in the cast cross section are avoided.

Source: E.F. Green of
North American Rockwell Corp.
under contract to
Marshall Space Flight Center
(MFS-18247)

Circle 18 on the Reader's Service Card.

Mechanical Properties of Bearium B-4 and Bearium B-10 at Three Temperatures

Test temp., °F	Tensile strength, 1000 lb/in² Yield, 0.2%	Tensile strength, 1000 lb/in² Ultimate	Elongation, %, in 1 in.	Elongation, %, in 0.5 in.	Reduction in area, %	Charpy-V ft/lb	Contraction, in./in.
			Bearium B-4				
70	12.9	21.8	11.0	12.0	16.8	5	0.0000
70	16.3	21.5	14.0	18.0	16.5	6	
70	13.3	22.9	14.0	17.0	15.0	7	
-100							0.00188
-320	21.9	36.8	19.5	24.0	16.0	6	0.00364
-320	19.4	32.2	19.0	26.0	22.5	6	
-320	20.4	32.1	17.5	24.0	18.9	5	
-423	25.4	34.8	14.0	16.0	11.5	8	0.00404
-423	22.4	35.4	20.0	22.0	14.5	8	
-423	24.4	38.6	18.0	14.0	13.7	8	
			Bearium B-10				
70	15.7	23.9	9.0	12.0	9.4	5	0.0000
70	17.0	25.0	8.0	10.0	9.4	4	
70	16.5	23.2	7.0	10.0	8.5	4	
-100							0.00192
-320	28.0	38.2	5.0	6.0	5.5	6	0.00388
-320	26.5	34.2	5.0	6.0	1.6	6	
-320	24.9	36.1	8.5	12.0	7.0	6	
-423	32.3	45.2	4.5	6.0	4.7	4	0.00439
-423		43.0	4.0	6.0	4.1	4	
-423	31.6	37.7	2.0	4.0	5.6	3	

NASA-Langley, 1971